

HI and dark matter in spiral galaxies

Albert Bosma

*Observatoire de Marseille, 2 Place Le Verrier, 13248 Marseille Cédex 4,
 France*

Abstract. We still do not have a “standard” model for the mass distribution of spiral galaxies. I review various methods used to delimit the range of values of the mass-to-light ratio of the disk, such as spiral structure criteria, the influence of bars, warped and flaring HI layers, velocity dispersions, and features in the rotation curve occurring just beyond the optical radius. It is not yet clear whether disks are maximal or not.

1. Ken Freeman’s early contribution to the dark matter problem

In his classic paper on exponential disks (Freeman, 1970), Ken presents a unifying scheme to describe the photometric properties of disk galaxies, using a simple law which describes the radial distribution of the surface brightness of the disk of a spiral or S0 galaxy reasonably well. He then works out the dynamics of such disks, and discusses issues related to disk formation. In the Appendix of that paper he concentrates on four galaxies, and points out that for two of them the available data hint at a discrepancy between the photometric scalelength of the disk and the expected peak of the rotation curve if the mass-to-light ratio of the disk is independent of radius. While for the LMC and the SMC there is no such discrepancy, the available data for M33 and NGC 300 do indicate one:

“For two of four systems with weak spheroidal components, the LMC and the SMC, the turnover radii of the rotation curves predicted from the photometrically derived gradients α appear to be consistent with those observed. For NGC 300 and M33, the 21-cm data give turnover points near the photometric edges of these systems. These data have relatively low spatial resolution; if they are correct, then there must be in these galaxies additional matter which is undetected, either optically or at 21 cm. Its mass must be at least as large as the mass of the detected galaxy, and its distribution must be quite different from the exponential distribution which holds for the optical galaxy.”

These remarks have been quoted by several authors retracing the history of the dark matter problem in spiral galaxies (e.g. Van Albada et al. 1985, Sciamia, 1993). It is actually interesting to examine how the interpretation of the data of these two galaxies changed as the instrumentation improved. This is of intellectual relevance to see how scientific debate advances with time : it is sometimes said that the dark matter problem constitutes a “revolution”, in the sense of Kuhn’s book (Kuhn 1962), or worse a “paradigm shift” – but then “what is a paradigm ?” (cf. Lakatos & Musgrave 1970) – so what is the contribution of Ken’s paper to this revolution ?

Early data on M33 are very confusing, and the most up-to-date information available in 1969 is summarized in an IAU Symposium published in Russian (cf. Demoulin et al. 1969). Dramatic improvements in the kinematical data on M33 were obtained in the early 70's, first through the work of the Cambridge HI group (Warner et al. 1973), and then by Rogstad et al. (1976). In the latter paper, one of the key characteristics of the HI distribution was pointed out : the HI layer is strongly warped beyond the edge of the optical disk. It turns out that if the points on the rotation curve in the warped part are ignored, as done by Kalnajs (1983), one can fit the rotation curve assuming the mass follows the light. If the rotation curve is extended with the HI points from the warped parts, this cannot be achieved anymore (Athanassoula et al. 1987, fig. 5).

For NGC 300, the early HI data are from a Parkes single dish study, (Shobbrook & Robinson 1967), and the surface photometry from De Vaucouleurs & Page (1962). Ken pointed out the discrepancy between the expected and observed turnover point of the rotation curve. HI data with much better angular resolution, analysed by Rogstad et al. (1979), show that the HI layer is strongly warped beyond the optical disk. Further study of this galaxy was done by a Puche, Carignan & Bosma (1990) – a student of a student of Ken, a student of Ken and a postdoc of Ken – which showed that there is indeed a mass discrepancy starting well within the optical radius, vindicating Ken's 1970 remark.

Thus we can say that Ken's study, as he reported it in the Appendix of his 1970 paper, pointed for the first time in an elegant manner to a mass discrepancy in a galaxy, based on a then novel general description - which is still standing - of how the luminosity is distributed in the disk (the exponential law), the idea that the mass-to-light ratio in a disk could well be constant, and appealing to HI studies to get information on galaxy rotation curves.

Dark halos came later (Ostriker & Peebles 1973), and their implication that spiral galaxy masses could really be large a year after (Einasto et al. 1974, Ostriker et al. 1974). These studies based themselves on the early work by Roberts & Rots (1973) and Rogstad & Shostak (1972). Yet at the observational side a long debate was spun about the validity of the data (in particular for M31, e.g. Roberts 1975, Baldwin 1975), the question whether fits with constant M/L were still possible (Emerson & Baldwin 1973, Baldwin 1975), the technical questions of sidelobes and beam smearing (e.g. discussions by Sancisi and Bosma following Salpeter 1977), and the interpretation of rotation curves derived from tilted ring models to describe warps (cf. discussion after Toomre 1977). Many of these problems were settled using high resolution HI data from the Westerbork telescope, accompanied by surface photometry and H α kinematics (Bosma 1978, 1981, Bosma & Van der Kruit 1979, Van der Kruit & Bosma 1978).

The work of Rubin et al. (1978), which later led to a series of papers on the rotation curves of Sc, Sb and Sa galaxies (Rubin et al. 1980, 1982, and 1985) was contemporary, but the HI data extends further out. Moreover, when, in the early 80s, everybody thought that dark halos are necessary to explain the flatness of rotation curves, Kalnajs (1983) showed that for optical rotation data, in four cases, there is no need for a dark halo, a conclusion corroborated for many more optical rotation curves by Kent (1986, 1987), Athanassoula et al. (1987), Buchhorn (1992) as reported in Freeman (1992), Moriondo et al. (1999), and Palunas & Williams (2000).

2. Current problems with mass models of spiral galaxies

2.1. “Standard” composite mass models

The current practice is to construct mass models using components : the bulge and disk components are derived from surface photometry, and a gas component from the radially averaged HI distribution. For the bulge and the disk it is assumed that each have a constant mass-to-light ratio, independent of radius. The molecular gas is implicitly assumed to follow the optical light. All components are quadratically added and then compared with the observed rotation curve. If there is a discrepancy, which is usually the case in the outer parts for extended HI rotation curves, a dark halo component is added.

Current debate centers on whether the disk is maximum, i.e. whether the value of the mass-to-light ratio of the disk is such that there is a maximum of mass in the disk, and thus a minimum amount of mass in the dark halo. As already mentioned above, for many optical rotation curves the radial extent is not large enough to show the presence of a dark halo, assuming that the disk is maximal. On the other hand, for many of the HI rotation curves the data come from tilted ring models (e.g. Rogstad et al. 1974) fitted to the warped part of the HI disk. Since warps are not really understood, there is always a lingering worry that such curves contain small systematics errors due to the neglect of systematic perpendicular motions.

2.2. Examination of the underlying hypotheses

Modern surface photometry (e.g. de Jong 1996) shows clearly that, if there is any colour gradient in disk galaxies, it is in the sense that disks become bluer in the outer parts. This means that the mass-to-light ratio in the disk could be decreasing with radius, which leads, in the composite models, to an increase in the concentration index of the dark halo. It seems best to use the K-band to get the stellar disk mass distribution, but there are as yet still few galaxies for which there are both the requisite K-band photometry and detailed HI and H α kinematics. Since the molecular gas scales better with the B-band (Young & Scoville 1982), a minor error can be introduced on this account.

A comparison between the HI rotation data by Verheijen (1997) for Ursa Major galaxies and my old collection of rotation curves (Bosma 1978) shows that, while it is easy to increase the number of galaxies for which there is HI data, the quality of the curves does not increase dramatically. This is due to the fact that it takes quite a lot of telescope time to get really good HI data, and for the more distant galaxies this is simply not available.

Beam smearing is another problem, which, while thoroughly understood in principle, is still playing an unnecessary large role in the discussion. Partly this is due to the unfortunate circumstance that for late type spirals the differences between the H α and HI rotation curves are not very large, and sometimes so small within the admittedly large errors of both datasets, that some people are misled into assuming that they can be ignored. This is sometimes justified *a posteriori* by taking a high resolution H α spectrum along the major axis, which agrees with the HI rotation curve in some cases, but not in others. Systematic programs are now underway to remedy this situation, using several techniques : long slit spectroscopy of emission lines such as H α (e.g. de Blok et al. 2001), 3D

imaging using Fabry-Pérot techniques (e.g. Corradi et al. 1991, Blais-Ouellette et al. 2001), or CO data from e.g. the BIMA interferometer (Wong 2000).

High resolution is crucial in the debate about the predicted slopes for the density profiles of the dark matter in LSB galaxies – inner power law slopes of order -1.5 (Moore et al. 1999, Fukushige & Makino 2001) or -1.0 (Navarro et al. 1996) – and those observed, which are of order 0.0, as argued e.g. in De Blok et al. (2001) and De Blok & Bosma (2001).

2.3. Is the dark matter directly associated with the HI ?

A relation between the HI gas mass density and the total mass density has been pointed out by Bosma (1978, 1981), who found that the ratio of gas mass surface density to total mass surface density becomes constant in the outer parts. This implies that the HI and the dark matter are somehow related, and inspired Pfenniger & Combes (1994) to postulate that the dark matter is in cold fractal molecular gas. In the context of composite mass models, the HI gas rotation curve is similar to the one of the dark halo, at least for maximum disk models, as discussed by Carignan et al. (1990). This is of course in some sense a restatement of the original result. Note that in this approach any molecular gas as inferred from the CO-distribution is assumed to scale as the light distribution.

Hoekstra et al. (2001) examine this further for a sample of well observed spiral galaxies already discussed in Broeils (1992). They calculate for 24 galaxies a histogram of the ratio $\Sigma_{\text{dark}}/\Sigma_{\text{gas}}$, determined by scaling up the HI rotation curve so that the observed rotation curve is fitted by a combination of disk, bulge, and scaled gas. The average ratio of $\Sigma_{\text{dark}}/\Sigma_{\text{gas}}$ is about 7, but with some spread. If one includes in this histogram the values given for dwarf galaxies determined by Swaters (1999), the distribution becomes quite dispersed, with no single peak.

3. Are galactic disks self-gravitating ?

In this section I will summarize the attempts to pin down more precisely the value of the mass-to-light ratio of the disk, in order to ascertain whether disks are maximal or not. A convenient way to put a number to this question is to consider a parameter γ , which is the ratio of the maximum amplitude of the disk rotation curve to that of the total rotation curve, evaluated at 2.2 disk scalelengths (which is roughly the radius of the peak of the disk rotation curve) :

$$\gamma = \left(\frac{V_{\text{disk}}}{V_{\text{total}}} \right)_{\text{at } R = 2.2 h} \quad (1)$$

Note that the maximum value γ can attain depends on whether there is a bulge present in the galaxy. If a bulge is present, γ can not reach unity even in the case of “maximum disk”. In what follows, I will rapidly review various methods to pin down γ , as an update to the discussion in Bosma (1999).

3.1. constraints from spiral structure

Swing amplifier criteria : Athanassoula et al. (1987) have discussed the application of spiral structure constraints to composite mass models. They examine

for each model whether there is the possibility of swing amplification based on the mechanism of spiral amplification discussed by Toomre (1981). A more graphical description is given in Bosma (1999). The physics of the swing amplifier depend on the shape of the rotation curve and on a characteristic X parameter, which in turn depends on the epicyclic frequency κ , the number of arms m , and the active surface mass density of the disk.

The range in mass-to-light ratio varies with about a factor of two if one requires swing amplification of the $m = 2$ perturbations : the lower limit is set by requiring that the disk is massive enough so that amplification of the $m = 2$ perturbations is just allowed, and an upper limit is set by requiring that amplification of the $m = 1$ perturbations is just prohibited. Usually the latter condition is fulfilled if one requires a model with maximum disk and a halo with non-hollow core. See Athanassoula et al. (1987) for more details.

Velocity signatures of spiral arm perturbations : Already in the M81 HI data obtained with the Westerbork telescope (Rots & Shane 1974) the effects of peculiar motions due to the spiral arms are clearly seen. These were modeled with a response calculation by Visser (1980), who did not use a dark halo in his models. Lately, Alfaro et al. (2001) show a single long-slit spectrum of the galaxy NGC 5427, where the presence of “wiggles” in the position-velocity curve are quite clearly associated with the spiral arms. It is clear that the presence of such wiggles indicates that the disk is self-gravitating enough to produce them.

In what promises to be the first of a series of papers, Kranz et al. (2001) present long-slit data for NGC 4254, a spiral galaxy in the Virgo cluster for which also HI data are available from Phookun et al. (1993). They try to reproduce the observed velocity perturbations with a stationary gas flow model using the K-band image of the galaxy as input to the evaluation of the disk part of the galactic potential. They find that a maximum disk model produces too large velocity perturbations, and put an upper limit on γ of 0.8. However, this galaxy is lopsided in the HI, the spiral may be evolving, and the small bar in the center of the galaxy might have a different pattern speed than the main spiral pattern. Moreover, the inclination may not be as low as the authors take it.

3.2. bar slow down due to dynamical friction

Debattista & Sellwood (1998, 2000) performed N-body simulations to study the slow down of a bar due to the dynamical friction with the surrounding dark halo. They argue that realistic bars can be made only if their disks are close to maximum. Athanassoula (this volume) addresses this subject anew. She finds that all strongly barred galaxies have maximum disks. Indeed, even if they start as sub-maximum, the rearrangement of the disk material due to the formation of the bar will lead to a maximum disk (cf. also Athanassoula & Misiriotis 2002).

3.3. fits of gas flow models to barred spirals

Weiner et al. (2000) modeled in detail the gas flow in the barred spiral NGC 4123, and find that the best fit to the velocity data requires a maximum disk model for the mass distribution. Note that here again the modelling is done as a response calculation for a stationary flow in the potential derived from an optical image. As in the case of NGC 4254, no time evolution has been considered.

3.4. warped and flaring HI disks

Data on the vertical axis ratio of the halo, c/a , have been collected and discussed by Olling and Merrifield (2000). Several methods are used, but for spirals the favourite method is that of the flaring of the HI layer (cf. Olling 1996). Relatively few galaxies have been studied this way, and more work on this is in progress (collaboration OBrien, Bosma & Freeman).

Warps also could in principle tell us something about the dark halo. If they are steady, and the halo is misaligned with the disk, MOND could in principle be ruled out. However, warps may well evolve rather rapidly, as simulations attest (Kuijken & Dubinski 1995). It is then not clear whether the presently observed HI warps can be used as a diagnostic of halo properties. Bosma (1991) showed that the frequency of warps is rather high, a result confirmed by more recent data of the WHISP survey. Bosma (1991) also discussed a relation between warps and halo properties : warps avoid the region where the ratio of halo core radius to optical radius is small. More work on this is needed.

3.5. stellar velocity dispersions in disks

Bosma (1999) and Fuchs (1999) report efforts to use stellar velocity dispersions to pin down γ , using data from Bottema (1993), or newer data of comparable quality. The series of assumptions made by Bottema (1993) were abandoned in those works, and the conclusion is that, strictly speaking, maximum disk models lead to Q -values slightly less than 1. However, the constant 3.36 in the formula for the critical velocity dispersion is dependent on the assumptions for the shape of the velocity ellipsoids, on the thickness of the layer, and on the presence of gas. Hence there is quite a bit of intrinsic uncertainty to this method. Moreover, a recent paper by Vega Beltran et al. (2001) shows that at the observational side the error bars are rather large. Nevertheless, further work on this is warranted, given the fundamental importance of velocity dispersions for the dynamics of spiral galaxies.

3.6. attempt to refute a MOND prediction

For a number of well observed galaxies, Begeman et al. (1991) have worked out maximum disk models as well as mass models based on MODified Newtonian Dynamics (Milgrom 1983). They conclude that MOND fits the data equally well, and determine the universal constant in this theory, the value of the critical acceleration parameter a_0 , to be $1.21 \cdot 10^{-8} \text{ cm}^{-2}$, by averaging the best fit values for a number of spirals. However, to fit the galaxy NGC 2841 with this value, it is required that its distance is about twice the distance inferred from the Hubble flow, i.e. 19.5 Mpc instead of 9.5 Mpc.

A recent study by Macri et al. (2001) determines the distance to this galaxy using Cepheids discovered on HST images. They derive a final value of 14.1 ± 1.5 Mpc. In collaboration with Erwin de Blok, I looked again at the data : we took some $H\alpha$ data in the inner parts, and tried to fit a mass model based on MOND. The model is uncertain in the inner parts; in the outer parts, its prediction is below the observed curve. But here again we are in the warped part of galaxy, hence we cannot yet rule out MOND with certainty using these data.

4. Extent of rotation curves

HI studies are limited to radii of about 30 - 50 kpc for a large galaxy, and rarely reach beyond that. The deepest HI image of a spiral galaxy is the one obtained by Van Gorkom et al. (unpublished), for the galaxy NGC 3198. As discussed in Maloney (1993), the HI in the outer parts drops relatively suddenly, but the total gas density may not drop as abruptly. Efforts to detect the ionized gas supposedly surrounding the HI at large radii have remained unsuccessful.

Further information at larger radii can be obtained by the study of satellites. Since most galaxies do not have many companions, a statistical treatment is in order. Zaritsky & White (1994) and Zaritsky et al. (1997) have done this for a large sample of spiral galaxies and conclude that dark halos are indeed extended. Weak lensing studies using data from the Sloan Digital Sky Survey (McKay et al. 2001) confirm these results and show that the size of a typical halo is about $260 h^{-1}$ kpc, which amounts, for a Hubble constant of $70 \text{ km s}^{-1} \text{ Mpc}^{-1}$, to 364 kpc – half the distance between our Galaxy and M31.

It may well be asked whether the rotation curve of such an extended halo stays flat, or whether a decline sets in. For our Galaxy, this question has been addressed in several papers (e.g. Zaritsky et al. 1989), and the result seem to be depend on the exact radial velocity of the Leo II system. For other galaxies, from HI data alone, the study of Verheijen (1997, 2001) shows for bright galaxies that there is a slight difference between V_{max} and V_{flat} , the latter referring to the rotation speed of the HI envelope. The Tully-Fisher relation tightens significantly when one uses the relation between the absolute magnitude in the K-band and V_{flat} instead of V_{max} . This comes on top of the tightening of the relation at the faint end by considering a “baryonic correction” (cf. Freeman 1998, McGaugh et al. 1999). Thus the Tully-Fisher relation is between the amount of baryons in a spiral galaxy and the rotation speed of its dark halo.

The difference between V_{max} and V_{flat} is not new, and for maximum disks it leads to the breakdown of the conspiracy between disk and halo (cf. Casertano & Van Gorkom 1991). Most often, the rotation curve drops rather suddenly just beyond the optical image, as already noted for NGC’s 5033 and 5055 by Bosma (1978, 1981). This feature could by itself be used to argue that disks are not far from maximum. However, an attempt to quantify this properly, for the galaxy NGC 4414 by Bosma (1998), shows that while a maximum disk model is preferred, a no $m = 2$ model cannot be excluded clearly. From statistics, both for a sample of galaxies with large rotation speeds I am working on, and one from the WHISP survey, I find that roughly 10 - 20 % of large spirals (Sa’s - Sc’s) have such a feature. This should be quantified further.

5. Conclusion

A comparison with Bosma (1999) and Sellwood (1999) shows where progress has been made on the issue of whether disks are self-gravitating: the results from Athanassoula et al. (1987) based on the swing amplifier criteria still stand, new results from Kranz et al. (2001) favour less than maximum disks, several studies argue that barred galaxies have maximum disks, and the use of stellar velocity dispersions is hampered by lack of good data. So not much progress ? Better

data will come from the gravitational lensing methods, which rather soon might come up with a clear answer. Until then, we can still try to improve things by getting better data and simulations along the lines discussed above.

Acknowledgments. Thanks are due to Lia Athanassoula for frequent discussions, and to Jerry Sellwood for recent exchanges of our points of view. Ken Freeman gave me freely his advice when I was a student in Groningen in the seventies (... better be a good observer than a lousy theoritician ...), arranged for a Research Fellowship for me in Stromlo after my thesis, and kept in contact over the years. In the nineties, we took up old collaborative work, and started new projects, some of which are still ongoing. I benefitted a lot from his comments on many topics. It is a pleasure to acknowledge also the kind hospitality Ken and Margaret have shown me on numerous occasions.

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Discussion

Van der Kruit: I would comment that to avoid confusion we should refrain from redefining the constant in the Toomre Q parameter, but rather require it to be at least some other value than 1. My question is the following. You ask : “are galaxy disks self-gravitating”, and answer probably yes for larger disks. What do you think the answer is for the Galactic disk in the solar neighbourhood ?

Bosma: OK for the comment. As for the question, the microlensing results in particular indicate that there is a lot of baryonic matter in the central parts of the Galaxy, so that there does not seem much room for a cuspy halo, as seemingly required by current models based on cosmological numerical simulations of cold dark matter, cf. a recent paper by Binney & Evans (astro-ph/0108505).

added after the meeting: The solar radius is roughly at 2.2 times the scalelength of the disk, and the “measured” disk surface density of $48 \text{ M}_{\odot} \text{ pc}^{-2}$ gives a peak speed of 126 km s^{-1} . It thus really matters whether the bulge/bar system is considered as part of the **disk**, and not as part of a spherical (and thus stabilizing) **bulge** component. This brings the circular speed of the combined bulge/disk to about 160 km/s at least. Thus γ could be of order 0.8 in our Galaxy, or even higher since the contribution of the molecular gas is quite uncertain.

King: As a spectator in this field rather than a participant, I get the overall impression that because of a lot of uncertainties (warps, asymmetries, etc., etc.) the estimation of the characteristics of dark halos is still very uncertain. Is this fair ?

Bosma: Yes, this is fair enough. I think that most people agree about the existence of the mass discrepancies, as brought out by the HI observations of extended gas disks, and many would say that implicates dark matter, but other than that there is not much agreement on how important the contribution of the dark matter is in the inner parts of disk galaxies.

King: You would then emphasize the qualitative conclusions, but not the quantitative ones.

Sellwood: A comment on the Kranz et al. paper : They assume a constant amplitude, constant pattern speed spiral, which will induce large amplitude responses at strong resonances. A more realistic transient spiral pattern may require more mass in the disk to produce the observed non-circular motions.

Bosma: As I said in the talk, the authors acknowledge that some of their assumptions are problematic, including the question of the stationarity of the spiral pattern for which they compute the gas response. Your suggestion may well be right. For this particular galaxy, NGC 4254, I am myself worried about the inclination they assume. But I understand that they have more data on other spirals, so it will be interesting to see what they come up with.